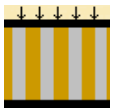
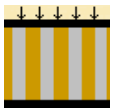


COLANY

User Manual



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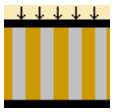
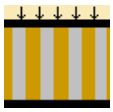


SYNOPSIS

COLANY computes the load-settlement response of a rigid foundation supported by a layer of clay stabilized with stone columns.

An example problem is considered. A complete hand solution to this problem and the results produced by COLANY are included. The hand solution is included in an attempt to ensure the correct interpretation of the results generated by COLANY.

Nigel Balaam
May 2012



1. INTRODUCTION

COLANY computes the settlement response of a rigid raft supported by a layer of clay which has been stabilized with a large number of stone columns. The results from an analytical solution (Balaam and Booker, 1981) for the settlement, assuming no yield occurs in the clay or column, are calculated. The program also computes the load-settlement response of the stabilized clay. The column is divided into a specified number of cylindrical elements and the load-deflection values are calculated at which each of the column elements yield. Therefore, the more elements the column is divided into the more points are plotted on the load-settlement curve. The analysis is described in Balaam and Booker (1985). Finally, the solution is computed for the settlement response of the stabilized clay when all the column elements have yielded. These solutions enable the complete load-settlement response to be predicted for the specified applied pressure.

In these analyses a 'unit cell' is considered and it consists of a stone column and the surrounding clay within the column's zone of influence. It is therefore assumed that the response of this 'unit cell' adequately represents the response of the clay layer stabilized by large numbers of stone columns.

2. PROBLEM DEFINITION

A regular pattern of stone columns can be analyzed by considering a typical column-clay unit (Figure 1). For a triangular arrangement each column has a hexagonal zone of influence whereas a square arrangement results in each column having a square zone of influence. In order to reduce the complexity of the analysis the zone of influence is approximated by a circle of effective diameter $d_e = 2b = 1.05s$ where s is the column spacing. A square arrangement of columns has $d_e = 1.13s$.

A consideration of the interaction between the stone columns and the surrounding clay indicates that the major principal stress direction will be close to the vertical direction and that while there may be significant yielding of the stone columns due to the high stress ratios, there will be little yield in the surrounding clay. This suggests that the problem can be idealized by assuming that the stone column is in a triaxial state but that perhaps part of it may yield, that there is no shear stress at the stone-column interface and that there is no failure in the surrounding clay so that its behavior is entirely elastic.

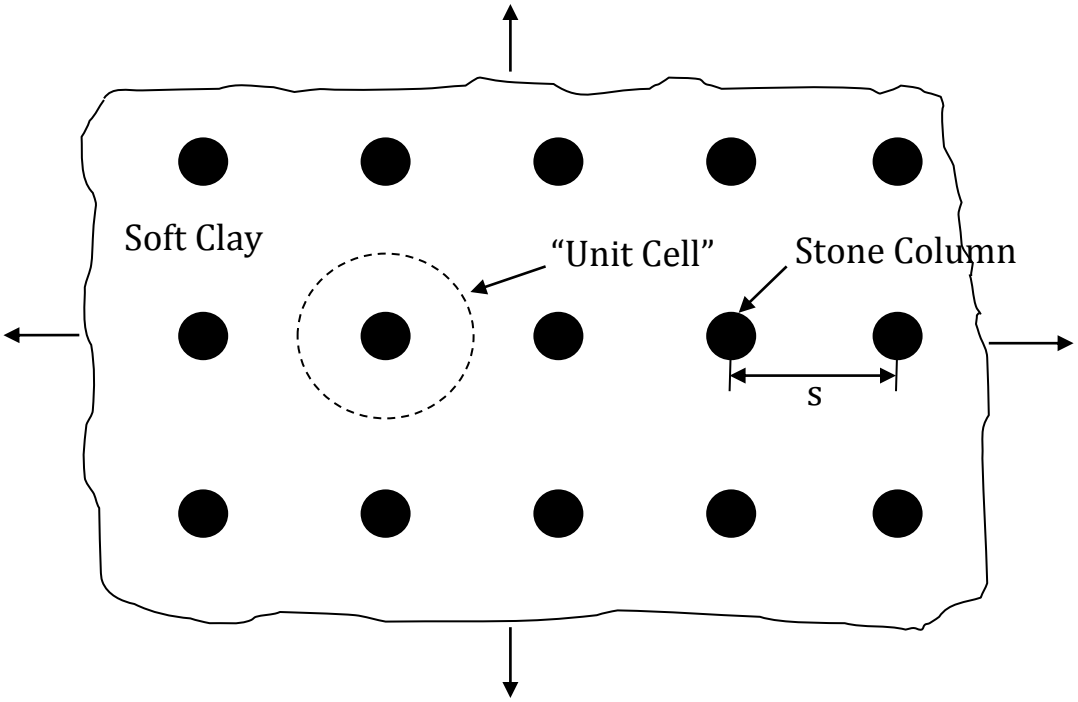


Figure 1a Plan: Stone Columns Installed in Large Numbers

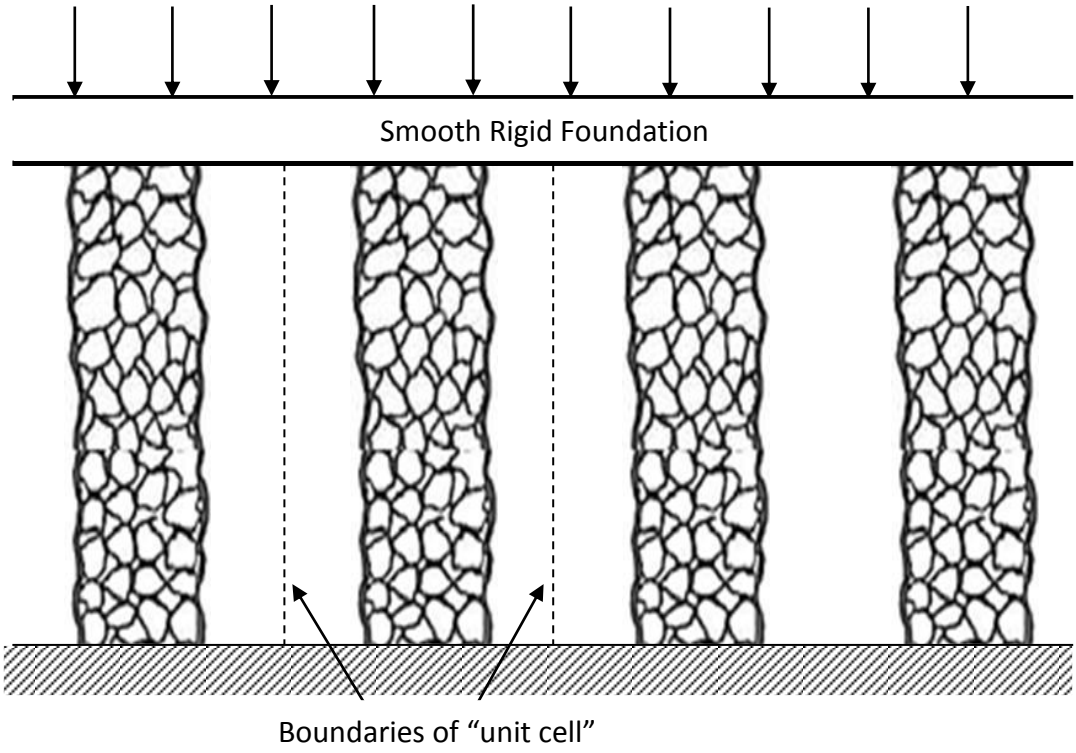


Figure 1b Elevation: Stone Columns Installed in Large Numbers

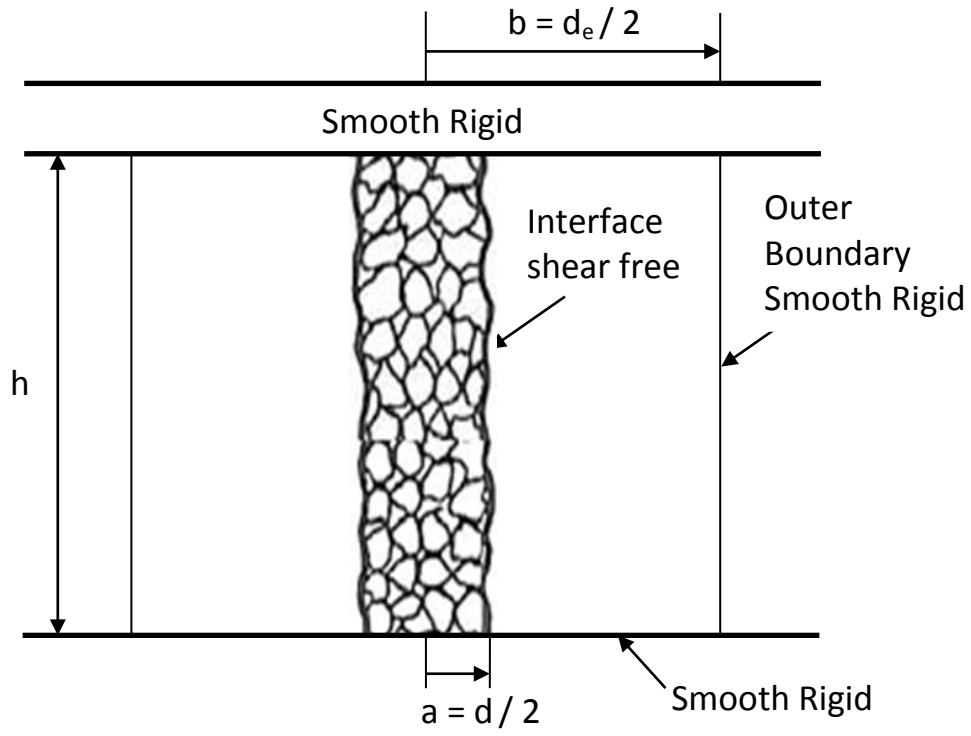
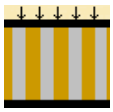


Figure 1c Boundary Conditions on "Unit Cell"

2.1 Material Properties

The material properties required for this analysis are:

Stone Column		Clay	
E_p	Young's modulus	E_s	Young's modulus
ν_p	Poisson's ratio	ν_s	Poisson's ratio
Ø	Angle of internal friction		
ψ	Dilatancy angle		
K_o	Coefficient of lateral stress		
γ_{sub}	Submerged unit weight		



2.2 Dimensions

The geometry is defined by these parameters:

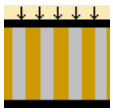
a Radius of the stone columns.

b Radius of the column's zone of influence.

h Depth of the clay layer and this is also the length of the stone columns because the analysis only considers columns constructed to the base of the clay layer.

2.3 Units

Any consistent set of units can be used, i.e., the dimensions specified must be consistent with the units for the applied pressure, q, and the applied pressure units must be consistent with the units specified for the Young's modulus of the stone and clay. The example problem uses metres for the dimensions and kPa for the applied pressure and Young's modulus.



3. EXAMPLE PROBLEM

3.1 Description

In this example a prediction is made of the settlement of a 40m diameter water tank supported by a rigid foundation founded on clay stabilized by stone columns. The maximum height of water stored in the tank is 20m. The stone columns have an average diameter of 1m and are installed on a triangular grid with a spacing of 1.95m. The water table is at the ground surface.

3.2 Hand Calculation

This hand calculation illustrates the use of the solutions (Balaam and Booker, 1985) and references to figures and the appendix in this section are from this paper.

Stone Columns

Length	L	25m
Diameter	d	1m
Spacing	s	1.95m on triangular grid
Young's modulus	E_p	60,000 kPa
Poisson's ratio	ν_p	0.3
Submerged unit weight	γ_{sub}	10 kN/m^3
Friction angle	Ø	35°
Dilatancy angle	ψ	0°
Coefficient of lateral stress	K_o	1.0

Clay

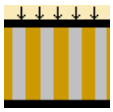
Young's modulus	E'_s	2,000 kPa
Poisson's ratio	ν'_s	0.3

Step 1: Calculation of one-dimensional settlement (no stabilization)

For the purpose of illustration the settlement of the tank founded on unstabilized clay can be estimated from 1-D settlement theory using an average m_v calculated from the average value of E'_s. The settlement S is

$$S = \varepsilon_Z \ h$$

$$\varepsilon_z = m_V \ \Delta\sigma_Z$$



For 1-D conditions

$$m_V = \frac{(1+\nu'_s)(1-2\nu'_s)}{E'_s(1-\nu'_s)}$$

$$= \frac{(1.3)(0.4)}{2000 \times 0.7}$$

$$m_V = 0.000371 \ m^2 / kN$$

The ε_z is given by

$$\varepsilon_z = m_V \ \Delta\sigma_Z$$

$= 0.000371 \times 20 \times 9.8$ The ε_z is given by

$= 0.0727$

The settlement

$$S = \varepsilon_Z \ h$$

$= 0.0727 \times 25$

$$\boxed{S = 1.82m}$$

<u>Step 2: Calculate settlement of tank founded on stabilized clay assuming stone columns and clay are elastic</u>

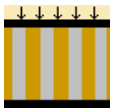
The elastic settlement is calculated using the equations in Appendix I.

i) Elastic parameters of stone column

$E_1 = E_p = 60{,}000$ kPa

$\nu_1 = \nu_p = 0.3$

$$\lambda_1 = \frac{\nu_1 \ E_1}{(1-2\nu_1)(1+\nu_1)} = \frac{0.3 \times 60000}{0.4 \times 1.3} = 34{,}615 \ kPa$$



$$G_1 = \frac{E_1}{2(1+\nu_1)} = \frac{60000}{2.6} = 23{,}077kPa$$

ii) Elastic parameters of clay

E_2 = E'_s = 2,000 kPa

ν_2 = ν'_s = 0.3

$$\lambda_1 = \frac{\nu_2 \ E_2}{(1-2\nu_2)(1+\nu_2)} = \frac{0.3 \times 2000}{0.4 \times 1.3} = 1{,}154\ kPa$$

$$G_2 = \frac{E_2}{2(1+\nu_2)} = \frac{2000}{2.6} = 769kPa$$

iii) Constant F (equation 10)

$$F = \frac{(\lambda_1 - \lambda_2)(b^2 - a^2)}{2[a^2(\lambda_2 + G_2 - \lambda_1 - G_1) + b^2(\lambda_1 + G_1 + G_2)]}$$

For a triangular spacing of 1.95m the diameter d_e of the "unit cell" is given by

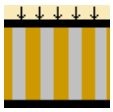
d_e = 1.05s =1.05 x 1.95 = 2.05m

b = d_e / 2 = 1.025m

The diameter d (=2a) of the stone columns is 1m.

$$F = \frac{(34615 - 1154) \times (1.025 \times 1.025 - 0.5 \times 0.5)}{2[0.5 \times 0.5 \times (1154 + 769 - 34615 - 23077) + 1.025 \times 1.025(34615 + 23077 + 769)]}$$

F = .282



iv) Strain [ε_z (=ε) from equation 11

$$q_A\, b^2 = [(\lambda_1 + 2G_1)a^2 + (\lambda_2 + 2G_2)(b^2 - a^2) - 2a^2(\lambda_1 - \lambda_2)\, F\,]\, \varepsilon$$

$$196 \times 1.025 \times 1.025 =$$

$$[(34615 + 2 \times 23077) \times 0.5 \times 0.5 + (1154 + 2 \times 769)(1.025 \times 1.025 - 0.5 \times 0.5) -]$$

$$[2 \times (34615 - 1154) \times 0.282]\ \varepsilon$$

$$\varepsilon = 0.01168$$

The elastic total final settlement of the tank founded on stabilized clay is

$$\delta_{elas} = 0.01168 \times 25$$

$$\boxed{Settlement = \ \delta_{elas} = 0.292m}$$

Step 3: Correct settlement to take account of contained yielding in the stone columns

The non-dimensional load level is:

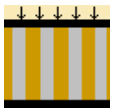
$$\frac{q_A}{\gamma_{sub}\, h} = \frac{20 \times 9.8}{10 \times 25} = 0.784$$

Referring to Figures 6 to 9 the following settlement correction factors can be tabulated.

TABLE 1 Settlement Correction Factors $\frac{\delta_{elas}}{\delta}$

		Ø	
		30°	40°
$\frac{d_e}{d}$	2	.34	.51
	3	.40	.49

Note: The tabulated values are for the modular ratio E_p / E'_s = 30. Linear interpolation for de / d = 2.05 and Ø = 35° results in a settlement correction factor;



$\frac{\delta_{elas}}{\delta}$ = 0.43

$\delta = \frac{0.292}{0.43\delta} = 0.679m$

Settlement of Tank = $\delta = 0.679m$

This settlement corresponds to a settlement ratio = 0.679 / 1.82 = 0.373.

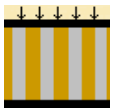
Some Comments

This example illustrates quantitatively that an analysis in which the stone columns and clay are assumed to be elastic throughout the range of applied load overestimates the effectiveness of the stone columns in reducing settlement.

The hand calculated value for the settlement ratio (= 0.373) is close to the value calculated by COLANY (= 0.40) and the error of 7% is expected considering the interpolation of values read from figures in the publication.

Finally, at sites where numerous tanks are constructed (e.g., refineries) or where the load is widespread the use of 1-D settlement theory is justified. However, in the example considered, if the tank were isolated the elastic settlement theory predicts a settlement of 1.37m when the clay is not stabilized. In these situations the settlement of the tank founded on the stabilized clay can be predicted with sufficient accuracy by applying the settlement reduction factor (= 0.373) to the elastic displacement theory settlement (1.37m). Therefore, for an isolated tank the predicted settlement theory is;

Settlement = $\delta = 0.373 \times 1.37$
= $0.512m$



4. COLANY

4.1 Data Entry

After starting COLANY and selecting "File/New Project" the data entry screen shown in Figure 2 is displayed. Figure 3 shows the data that has been entered for the example problem described in Section 3.

The data is self-explanatory except the value of 20 entered for the number of elements. This is the number of equal sized cylindrical elements the column is divided into and is used to calculate the progressive yielding of the column. For example, when 20 elements are specified there are 21 points defining the load-settlement response, one for each element yielding and the final, 21st point, defining the response when the column has fully yielded.

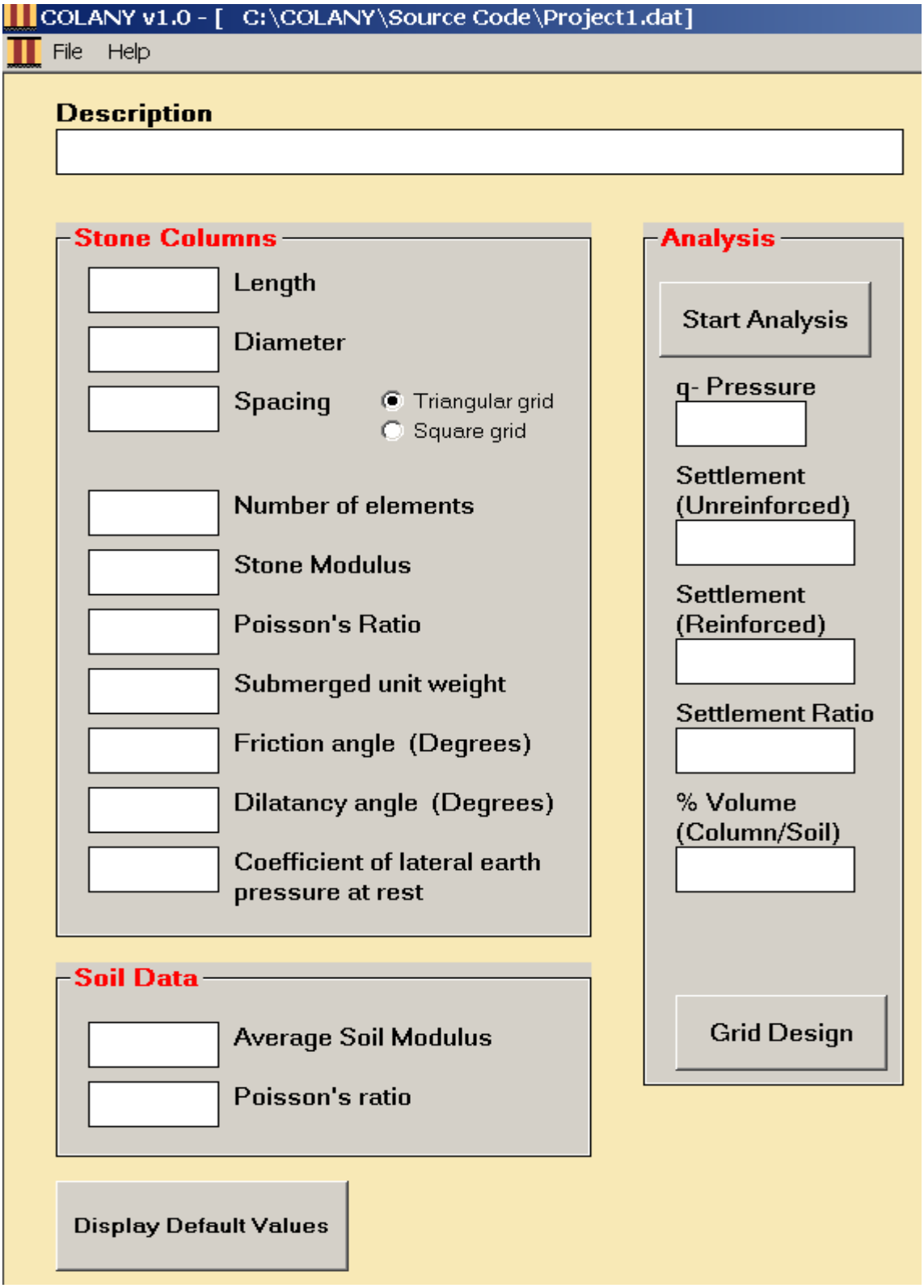


Figure 2 Data Entry Screen

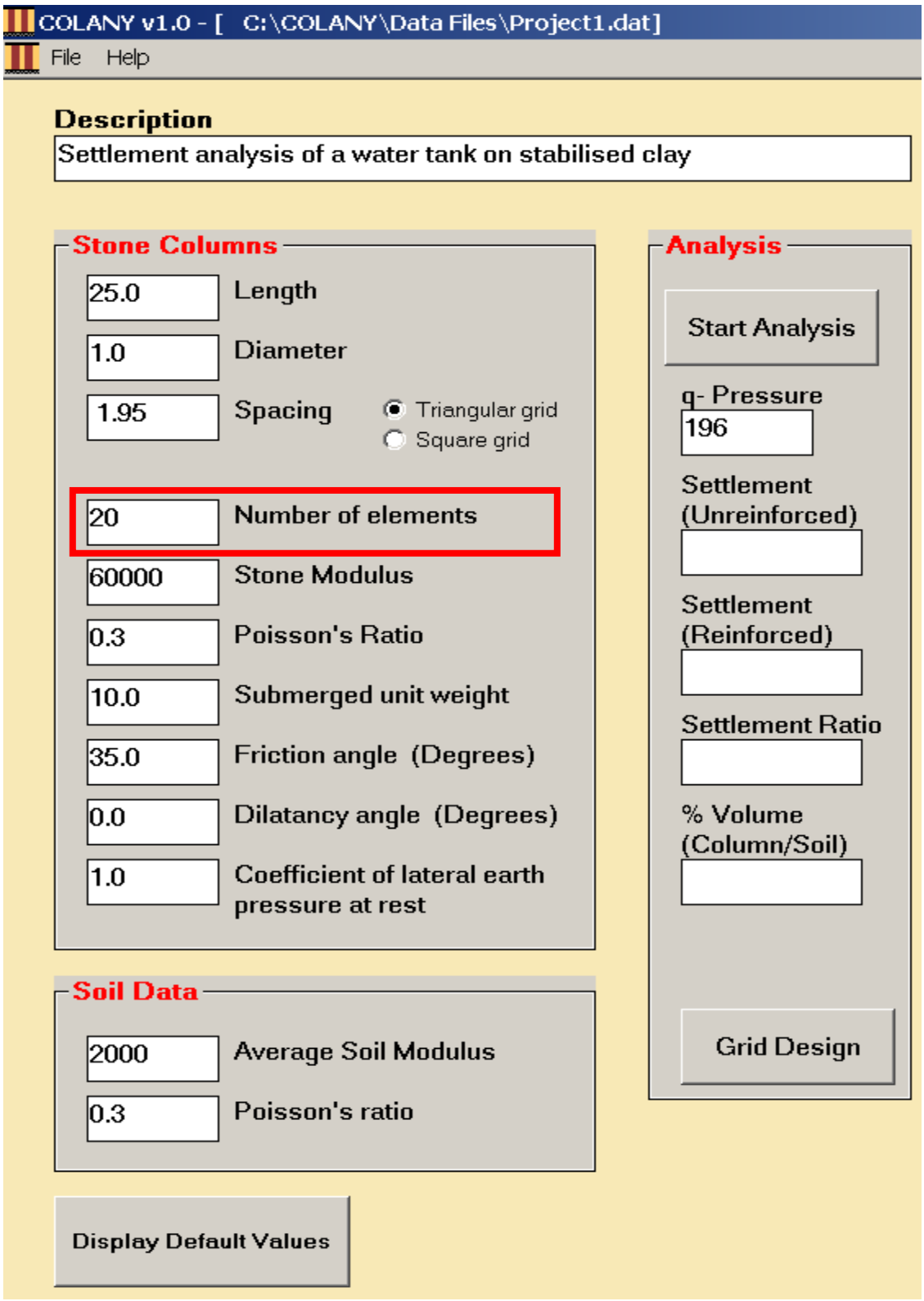
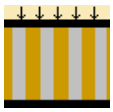
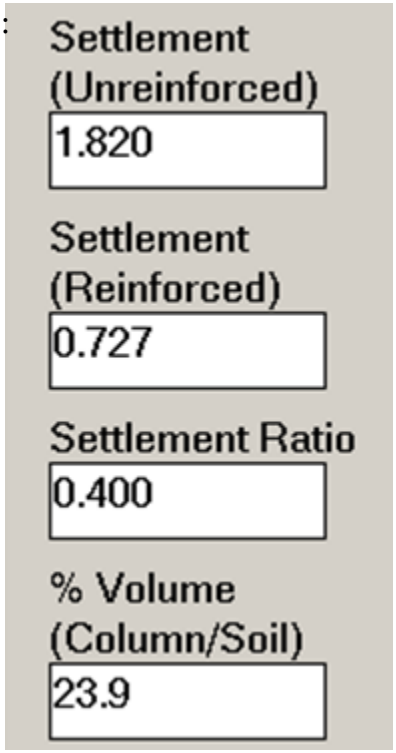


Figure 3 Example Problem Data



4.2 Results

The analysis is performed when the 'Start Analysis' command button is clicked. The results are shown in Figure 4. The results are



1-D settlement of unreinforced clay = 1.82m.

Settlement of stone column reinforced clay = 0.727m.

Settlement ratio = 0.727 / 1.82 = 0.400

Ratio of stone column volume to total volume of the unreinforced clay layer = 23.9% .

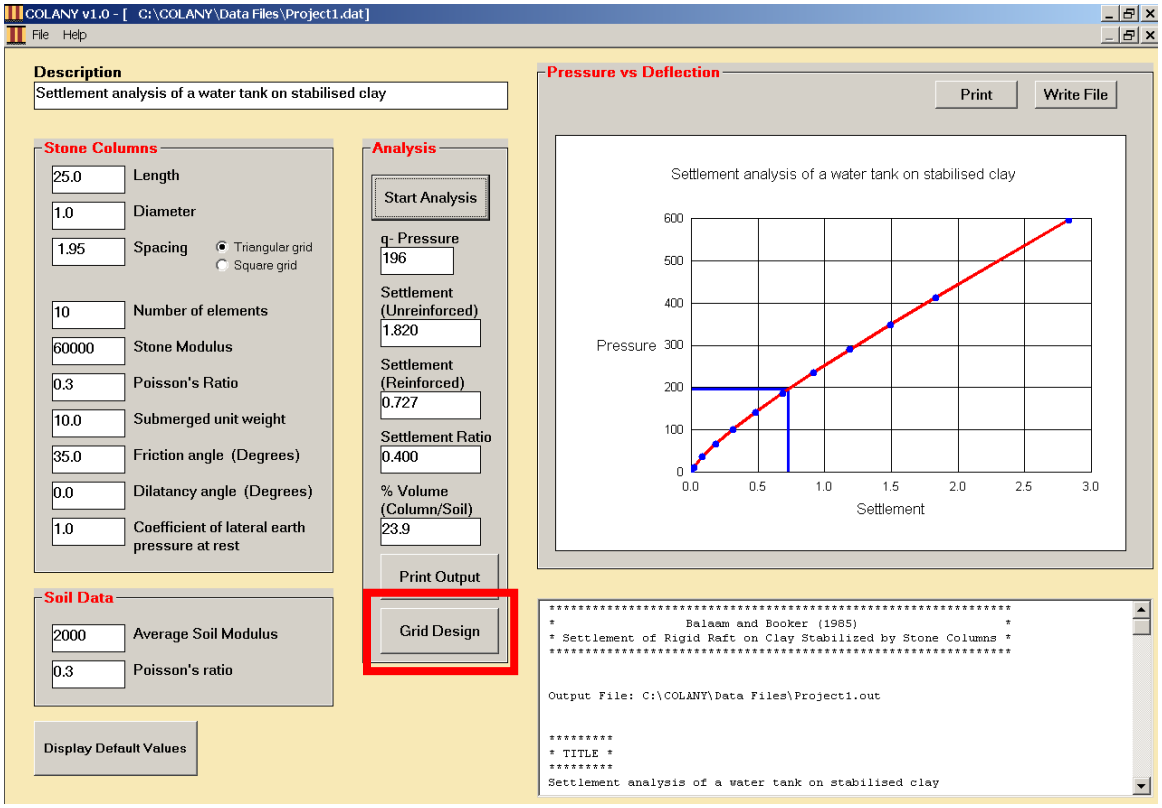
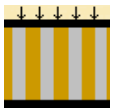


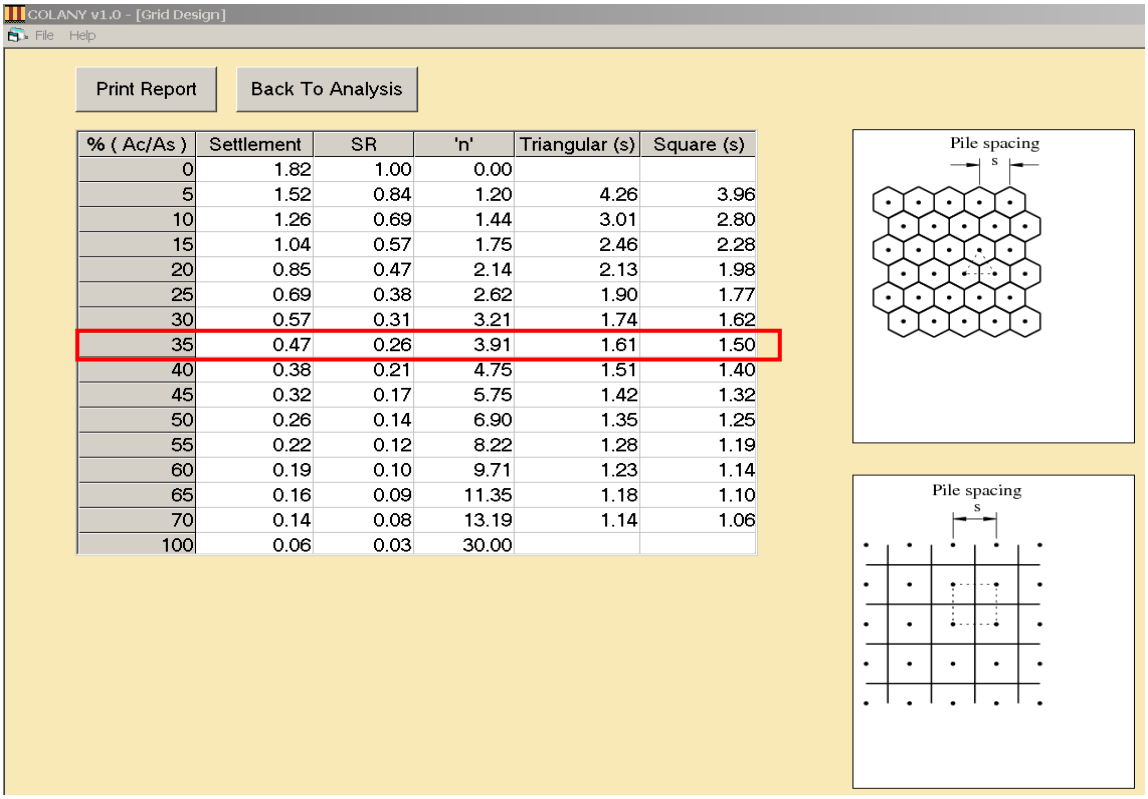
Figure 4 Screen Displayed After 'Start Analysis' Button Clicked



4.2 Grid Design

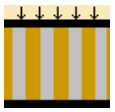
When the "Grid Design" button (highlighted in Figure 4) is clicked multiple analyses of the problem are performed. The loading, column diameter, column length, material properties etc. all remain unchanged. The only parameter that is changed is the column spacing and analyses are performed for both triangular and square arrangements of the columns. These multiple analyses are summarized in tabular form and are shown in Figure 5. The first row in the table corresponds to the unreinforced soil and then each row below this summarizes the results for a 5% increases in stone column material. The values in the grid can be used to select an appropriate arrangement and spacing of columns to meet a specific design criterion. For example, in the example problem considered in this manual, if the maximum allowable settlement of the tank is 0.5m then referring to the highlighted row in Figure 5 this arrangement of columns would satisfy the requirement because the predicted settlement is 0.47m The values on this row are;

% (Ac/As)	35% of the soil has to be replaced with stone columns.
Settlement	0.47m (satisfies maximum allowable settlement = 0.5m)
SR	Settlement Ratio = Settlement of Reinforced Soil / Settlement Unreinforced
'n'	Improvement factor. n = 1 / SR
Triangular(s)	Columns on triangular grid spaced at 1.61m. Specify 1.6m.
Square	Columns on square grid spaced at 1.5m.



% (Ac/As)	Settlement	SR	'n'	Triangular (s)	Square (s)
0	1.82	1.00	0.00		
5	1.52	0.84	1.20	4.26	3.96
10	1.26	0.69	1.44	3.01	2.80
15	1.04	0.57	1.75	2.46	2.28
20	0.85	0.47	2.14	2.13	1.98
25	0.69	0.38	2.62	1.90	1.77
30	0.57	0.31	3.21	1.74	1.62
35	0.47	0.26	3.91	1.61	1.50
40	0.38	0.21	4.75	1.51	1.40
45	0.32	0.17	5.75	1.42	1.32
50	0.26	0.14	6.90	1.35	1.25
55	0.22	0.12	8.22	1.28	1.19
60	0.19	0.10	9.71	1.23	1.14
65	0.16	0.09	11.35	1.18	1.10
70	0.14	0.08	13.19	1.14	1.06
100	0.06	0.03	30.00		

Figure 5 Grid Design Screen



The file produced for the example problem when the “Print Report” button is pressed is:

COLANY v1.0 Grid Design Balaam & Booker (1985)

Job Description

Settlement analysis of a water tank on stabilised clay

Loading

Applied Pressure (q) = 196.0

Stone Columns

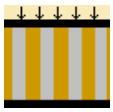
Length of column (h) = 25.0
Diameter(d) = 1.0
Friction angle(phi) = 35.0
Submerged unit weight = 10.0
Coefficient(Ko) = 1.0
Dilatancy angle(psi) = 0.0
Young's Modulus = 60000.0
Poisson's ratio = 0.3

Soil

Young's Modulus = 2000.0
Poisson's ratio = 0.3

%(Ac/As)	Settlement	SR	n	Triangular(s)	Square(s)
0	1.82	1.00	0.00	Unreinforced soil	
5	1.52	0.84	1.20	4.26	3.96
10	1.26	0.69	1.44	3.01	2.80
15	1.04	0.57	1.75	2.46	2.28
20	0.85	0.47	2.14	2.13	1.98
25	0.69	0.38	2.62	1.90	1.77
30	0.57	0.31	3.21	1.74	1.62
35	0.47	0.26	3.91	1.61	1.50
40	0.38	0.21	4.75	1.51	1.40
45	0.32	0.17	5.75	1.42	1.32
50	0.26	0.14	6.90	1.35	1.25
55	0.22	0.12	8.22	1.28	1.19
60	0.19	0.10	9.71	1.23	1.14
65	0.16	0.09	11.35	1.18	1.10
70	0.14	0.08	13.19	1.14	1.06
100	0.06	0.03	30.00	Soil fully replaced	

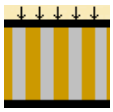
Ac = Area of columns
As = Area of soil
SR = Settlement Ratio = Settlement(Reinforced)/Settlement(Unreinforced)
n = Improvement factor = Settlement(Unreinforced)/Settlement(Reinforced)
s = Column spacing



4.3 Data File – Example Problem

The content of the data file for the example problem is:

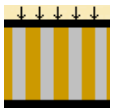
```
[TITLE]
Settlement analysis of a water tank on stabilised clay

[APPLIED PRESSURE]
196

[COLUMN LENGTH]
25.0

[COLUMN DIAMETER]
1.0

[COLUMN SPACING]
 1.95

[COLUMN PATTEREN  1=Triangular  2=Square]
 1

[NUMBER OF ELEMENTS]
20

[COLUMN MODULUS]
60000

[COLUMN POISSON'S RATIO]
0.3

[COLUMN SUBMERGED UNIT WEIGHT]
10.0

[COLUMN FRICTION ANGLE]
35.0

[COLUMN DILATANCY ANGLE]
0.0

[COLUMN COEFFICIENT OF LATERAL EARTH PRESSURE]
1.0

[SOIL MODULUS]
2000

[SOIL POISSON'S RATIO]
0.3
```



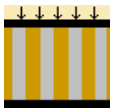
4.4 Output File – Example Problem

The content of the output file for the example problem is:

```
*****************************************************************
 *                   Balaam and Booker (1985)                    *
 * Settlement of Rigid Raft on Clay Stabilized by Stone Columns *
 *****************************************************************


 Output File: C:\COLANY\Data Files\Manual.out


 *********
 * TITLE *
 *********
 Settlement analysis of a water tank on stabilised clay

 ************
 * GEOMETRY *
 ************

 Triangular Grid
 Spacing =     1.95

 a =    0.500
 b =    1.024
 de =    2.047


 *****************
 * STONE COLUMNS *
 *****************

 Length of column (h)  =     25.00
 Diameter (d)          =      1.00
 Number of elements    =        20
 Friction angle (phi)  =     35.00
 Submerged unit weight =     10.00
 Coefficient (K0)      =      1.00
 Dilatancy angle (psi) =      0.00
 Young's Modulus       =   60000.0
 Poisson's ratio       =      0.30


 ********
 * CLAY *
 ********

 Young's Modulus =    2000.00
 Poisson's ratio =       0.30
```



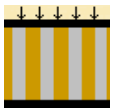
```
********************
* ELASTIC SOLUTION *
********************


Elastic Solution  (Balaam & Booker 1981)
For unit applied pressure the solution is :

STONE COLUMN:
Radial displacement u(r) =   8.3898E-06
Sigma(rr) =   1.2275E-01
Sigma(00) =   1.2275E-01
Sigma(zz) =   3.6423E+00
Strain (zz) =   5.9478E-05
Surface deflection (delta) =   1.4870E-03

CLAY :
Sigma(zz) =   1.7226E-01


*********************************
* INITIAL EFFECTIVE STRESS STATE *
*********************************

Element    Sigma(zz)'     Sigma(rr)'
  1           6.25          6.25
  2          18.75         18.75
  3          31.25         31.25
  4          43.75         43.75
  5          56.25         56.25
  6          68.75         68.75
  7          81.25         81.25
  8          93.75         93.75
  9         106.25        106.25
 10         118.75        118.75
 11         131.25        131.25
 12         143.75        143.75
 13         156.25        156.25
 14         168.75        168.75
 15         181.25        181.25
 16         193.75        193.75
 17         206.25        206.25
 18         218.75        218.75
 19         231.25        231.25
 20         243.75        243.75
```



```
****************************
* LOAD-SETTLEMENT RESPONSE *
****************************
```

Load Step	Average Pressure	Surface Settlement	Total Load	Column Load	Soil Load
1	5.27	0.0078	17.36	15.08	2.28
2	16.51	0.0308	54.36	45.30	9.06
3	29.39	0.0633	96.76	78.05	18.71
4	43.45	0.1043	143.05	112.10	30.96
5	58.69	0.1538	193.26	147.46	45.80
6	75.13	0.2119	247.37	184.13	63.24
7	92.75	0.2786	305.40	222.12	83.28
8	111.56	0.3538	367.33	261.42	105.91
9	131.56	0.4375	433.18	302.03	131.15
10	152.75	0.5298	502.93	343.96	158.97
11	175.12	0.6307	576.60	387.20	189.40
12	198.68	0.7401	654.17	431.75	222.42
13	223.43	0.8580	735.65	477.61	258.04
14	249.36	0.9845	821.05	524.79	296.26
15	276.48	1.1195	910.35	573.27	337.08
16	304.79	1.2631	1003.56	623.08	380.49
17	334.29	1.4153	1100.69	674.19	426.50
18	364.98	1.5759	1201.72	726.62	475.11
19	396.85	1.7452	1306.67	780.36	526.31
20	429.97	1.9233	1415.71	835.50	580.20

```
************************
* COLUMN FULLY PLASTIC *
************************

For an increment in deflection of 1.0
(ie. an increment in strain of   4.0000E-02 )
the following increments occur :

CLAY :
d Sigma(rr) =    104.3
d Sigma(zz) =    120.7
d Load (clay)=    302.7

COLUMN :
d u(r) =   9.0111E-03
d Sigma(rr) =    104.3
d Sigma(zz) =    384.8
d Load (column) =    302.2


d Load (clay+column) =    604.9
d q(A) =    183.7
```



5. REFERENCES

Balaam, N.P. and Booker, J.R. (1981), "Analysis of Rigid Rafts Supported by Granular Piles", International Journal for Numerical Methods in Geomechanics, Vol.5, pp. 379-403.

Balaam, N.P. and Booker, J.R. (1985), "Effect of Stone Column Yield on Settlement of Rigid Foundations in Stabilized Clay", International Journal for Numerical Methods in Geomechanics, Vol.9, pp. 331-351.